BI-TP 2002/20
DESY 02-117
August 2002

The H dibaryon on the lattice

I. Wetzorke[a] and F. Karsch[b]

[a]NIC / DESY Zeuthen, Platanenallee 6, 15738 Zeuthen, Germany

[b]Fakultät für Physik, Universität Bielefeld, 33615 Bielefeld, Germany

We present our final results for the mass of the six quark flavor singlet state ($J^P = 0^+$, $S = -2$) called H dibaryon, which would be the lightest possible strangelet in the context of strange quark matter. The calculations are performed in quenched QCD on $(8-24)^3 \times 30$ lattices with the (1,2) Symanzik improved gauge action and the clover fermion action. Furthermore the fuzzing technique for the fermion fields and smearing of the gauge fields is applied in order to enhance the overlap with the ground state. Depending on the lattice size we observe an H mass slightly above or comparable with the $\Lambda\Lambda$ threshold for strong decay. Therefore a bound H dibaryon state seemed to be ruled out by our simulation.

1. INTRODUCTION

A bound six quark state ($uuddss$) called H dibaryon with a mass 81 MeV below the 2231 MeV $\Lambda\Lambda$ threshold for strong decay was predicted in a bag model calculation in 1977 [1]. The H dibaryon is the lightest possible SU(3) flavor singlet state with spin zero, strangeness -2 and $J^P = 0^+$. It has been speculated that the H dibaryon could form a Bose condensate in nuclear matter prior to the quark-hadron phase transition of QCD at high density. In the context of strange quark matter the H dibaryon was suggested as a candidate for the smallest strangelet [2], which became relevant in the discussion on disaster scenarios at RHIC [3].

In the 25 years after the initial prediction of a stable H dibaryon state numerous searches for this particle were performed. On the theoretical side this involved various model calculations, QCD sum rules and perturbative calculations including color-spin (One-Gluon-Exchange) or flavor-spin (Instanton Induced Interaction, Goldstone-Boson-Exchange) dependent q-q interactions. The resulting H dibaryon masses scatter in a range of $\mathcal{O}(100 \text{ MeV})$ around the $\Lambda\Lambda$ threshold. Moreover experimental searches showed almost no evidence for a bound H dibaryon. The review article [4] summarizes both the theoretical and experimental attempts to verify the existence and stability of the H dibaryon.

In the 1980's two lattice calculations [5,6] reported contradictory results on m_H, but both simulations suffered from heavy quark masses and low statistics. In 1999 yet another calculation [7] overcame these problems and concluded that the H dibaryon state is unbound in the infinite volume limit. Our aim was to check these results with refined methods, which includes on the one hand the use of improved gauge and fermion actions and on the other hand the use of smearing and fuzzing techniques to enhance the overlap with the ground state.

2. DETAILS OF THE SIMULATION

We performed our calculations with the (1,2) Symanzik improved gauge action and the tree-level improved clover fermion action on rather coarse lattices ($\beta = 4.1$, $a = 0.177(8)$ fm) of the size $(8-24)^3 \times 30$ in order to study the large six quark object with an adequate spatial lattice extent. Depending on the lattice size we generated 40 to 120 configurations on which the propagators for three to five kappa values for the degenerate u/d and heavier s quark masses in the range of 30 to 250 MeV were calculated.

The particle masses are obtained from exponential decrease of the correlation function $G(\tau) = \int d^3x \langle\, \mathcal{O}(\vec{x},\tau)\mathcal{O}^\dagger(\vec{0},0)\,\rangle$ for the appropriate operators of the Λ baryon and the H dibaryon [8] (color indices: roman letters, spinor indices: greek letters):

$$
\begin{aligned}
\mathcal{O}_\Lambda(x) &= \epsilon_{abc}(C\gamma_5)_{\beta\gamma}[u^a_\alpha(x)d^b_\beta(x)s^c_\gamma(x) \\
&\quad +d^a_\alpha(x)s^b_\beta(x)u^c_\gamma(x) - 2s^a_\alpha(x)u^b_\beta(x)d^c_\gamma(x)] \\
\mathcal{O}_H(x) &= 3(udsuds) - 3(ussudd) - 3(dssduu) \\
(\mathsf{abcdef}) &= \epsilon_{abc}\epsilon_{def}(C\gamma_5)_{\alpha\beta}(C\gamma_5)_{\gamma\delta}(C\gamma_5)_{\epsilon\phi} \\
&\quad * \mathsf{a}^a_\alpha(x)\mathsf{b}^b_\beta(x)\mathsf{c}^c_\epsilon(x)\mathsf{d}^d_\gamma(x)\mathsf{e}^e_\delta(x)\mathsf{f}^f_\phi(x)
\end{aligned}
$$

In addition to the Λ and H dibaryon we calculated the correlators of the (non-)strange mesons π, ρ, K, K^* as well as the baryons N and Σ. These particle masses were used for scale setting and comparison to the experimental spectrum. The degenerate u/d-quark mass is fixed by the ratios m_π/m_N, $m_\pi/\sqrt{\sigma}$ and $m_N/\sqrt{\sigma}$ yielding a common value of κ_{ud}=0.1490(1). In order to eliminate the quenching effects most efficiently in the setting of the strange quark mass, we determined a mean value of κ_s=0.1417(2) by averaging over the κ_s-values obtained from the particle ratios m_Λ/m_N, m_Σ/m_N and m_{K^*}/m_N. Furthermore the dependence of the mass difference $m_H - 2m_\Lambda$ on the three possible ways of fixing κ_s is investigated in section 3.

2.1. Smearing & Fuzzing

A good projection to the ground state is very important for a reliable extraction of the particle masses. A better overlap with the ground state can be achieved by the iterative smearing of the gauge links and the application of the fuzzing technique for the fermion fields [9] taking the physical size of the particle into account. The separation of a quark-quark pair by a suitable distance, the so-called fuzzing radius, thus will maximize the ground state contribution relative to the ones of the excited states already at small Euclidean time separations. We apply this method for the calculation of the meson, baryon and dibaryon correlators. We could show [10] that the largest plateau in the effective mass is obtained for four fuzzed quarks, actually the four light quarks inside the H dibaryon, employing a fuzzing radius of about 0.7 fm. For the strange mesons (baryons) we use the one (two) light quark field(s) fuzzed with the same fuzzing radius.

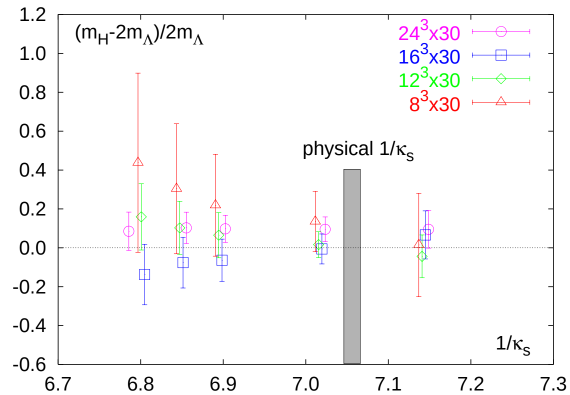

Figure 1. Dependence of the mass difference on the lattice size and κ_s at physical κ_{ud}

3. RESULTS

The particle masses calculated for different kappa values are first extrapolated linearly to the physical κ_{ud} value while keeping κ_s fixed. The final result is determined by interpolating to the mean κ_s value, where the physical scale is fixed by the particle ratios as mentioned above. The obtained K^*, Σ and Λ masses are compared to the experimental values and show a deviation less than 8 % except for the smallest lattice size. Such a variance can be considered as usual quenching effect. Relatively strong finite size effects are observed for the smallest lattice size $L = 8a = 1.4$ fm. Whereas the strange mesons masses obtained on this lattice are only slightly higher than the ones on the larger lattices, this effect is more pronounced for the heavier baryon masses. For the six quark H dibaryon state a very strong influence of the spatial lattice size is observed. In figure 1 we show the mass difference $m_H - 2m_\Lambda$ at physical κ_{ud} for the four different lattice sizes. The grey band indicates the mean κ_s value as explained in section 2. The points are slightly displaced in κ_s for better visibility. The slope of the κ_s dependence is obviously quite different for varying lattice volume, but the mass difference in the physical region is nevertheless quite similar and near zero for all investigated lattice sizes.

In order to clarify the evidence for an unbound

H dibaryon state, a closer look at the dependence of the scale setting by the particle ratios seems helpful. Figure 2 shows the mass difference for all lattice sizes using the Λ, Σ or K^* masses as input to fix κ_s as mentioned above. The points are again a bit displaced - this time in the spatial lattice extent L. Moreover the interpolation to the mean value of $\kappa_s = 0.1417(2)$ and the previous results of Pochinsky et al. [7] are shown to allow a direct comparison. The strong finite size effects are probably the reason for the overestimated mass difference observed for the smallest lattice size. On the intermediate lattice sizes all values of $m_H - 2m_\Lambda$ are compatible with zero independent of the particle ratio used as input. On the largest lattice with $L/a = 24$ the values are slightly higher, but may come closer to zero with larger statistics. Therefore our simulations provide no evidence of a bound H dibaryon state for the investigated lattice sizes. A detailed table of the particle masses for the respective choice of input particle will be given soon in a longer write-up [11].

Finally we want to compare our findings with the previous lattice results [7], which were also obtained on $L/a = 16$ and 24 lattices but with a smaller lattice spacing of 0.13(3) fm. At a spatial size of about 2 fm the former result lies at bit below our values, while a good agreement can be observed for a larger extent of $L \approx 3$ fm. Hence a common conclusion arises from the recent and present studies: The H dibaryon does not exist as stable particle in the vacuum, at least in the limit of quenched QCD.

4. SUMMARY & OUTLOOK

We have presented the results of the first lattice investigation on the H dibaryon state employing improved gauge and fermion actions, relatively light quark masses as well as smearing and fuzzing techniques to enhance the overlap with the ground state of the particle. We observe a H dibaryon mass slightly above or comparable with the $\Lambda\Lambda$ threshold for strong decay on all lattice sizes. We thus provide further evidence for an unbound H dibaryon state consisting of two lambda baryons.

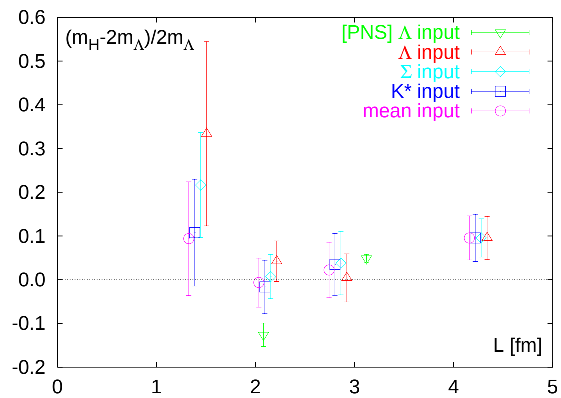

Figure 2. Dependence of the mass difference on the choice of scale setting particle at physical κ_{ud} and κ_s ([PNS] values for Λ input values are taken from [7].)

A final remark concerns the relative error of the H dibaryon correlation function, which is rising only linearly compared to the Λ baryon correlator. This observation raises the hope that simulations of larger strangelets or even multi-quark clusters might be possible in the future.

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